THE COLOR SENSATIONS OF THE PARTIALLY COLOR-BLIND, A CRITICISM OF CURRENT TEACHING

By SAMUEL P. HAYES, Ph. D.,[1] Mount Holyoke College

A. INTRODUCTION

Although the existence of color-blindness has been known since 1777 (32, *cf.* 76), and although large numbers of cases have been studied and described (19) during the century and a quarter which has elapsed since that date, the general topic of color-blindness is still in a state which many psychologists consider to be most disgraceful to their science. One reason for this backward condition is undoubtedly to be found in the extreme complexity of the subject, and the enormous variation from case to case; but an even greater obstacle to the progress of knowledge has been the almost universal practice of studying and classifying cases under the domination of some pre-conceived color-theory (36). Perhaps the most notable example of this practice is to be found in the description of the sensations of the red-blind, which Helmholtz gives in the first edition of his *Optik*.[2] But even to-day, after fifty additional years of extended observation and experimentation upon color-defectives, many psychologists seem disposed to discuss the topic in such a loose and superficial fashion as will make it accord with the color theory which they have espoused, rather than to work out a full and clear

[1]The writer wishes to express his gratitude to Professors E. B. Titchener and J. W. Baird for much helpful criticism and suggestion.

[2]Helmholtz (18, p. 298) states that red, if seen at all, is seen as a weak green; yellow, as a stronger, saturated green; green, as a whitish green; blue and violet, as blue; and white as greenish blue. Holmgren (quoted 33, p. 29) describes the sensations of the green-blind and of the violet blind, in the same fashion; his procedure is essentially a logical process, and his description is an *inference* as to how the defective retina *must* see colors when its green-sensing or its violet-sensing fibres are lacking.

statement of the facts thus far known, regardless of their theoretical implications.

Ever since the work of Seebeck (69), in the early part of the nineteenth century, it has been customary to divide the partially color-blinds into two or more classes,—the writers of the Helmholtzian school tending to distinguish *three* groups, while those who advocate a four color-element theory tend to distinguish *two*. Seebeck regarded the shortening of the spectrum, which he found in certain cases, as a fundamental basis of differentiation; and, in present-day usage, the two best established groups of partially color-blinds are those which are distinguished by the different lengths of their spectrums: *Deuteranopes*, whose color-system is reduced to blue, yellow and grey, but who see color throughout the whole length of the spectrum; and *Protanopes*, who likewise see only blue, yellow and grey, but whose spectrum is shortened at the red-end, and who show the Purkinje phenomenon in ordinary light, *i e.*, whose region of maximum brightness is displaced from yellow toward blue (40). Authorities disagree upon the question of the existence of a third group of partially color-blinds—*Tritanopes*, whose color system is reduced to red and green (40, 71, 74). All three groups are commonly referred to as *dichromates*, because their color system is assumed to be reduced to two colors.

Unfortunately this simple classification does not provide for all the cases of color deficiency which have been discovered. Seebeck (69, pp. 216 ff.) found mild cases of color deficiency which he was loath to include in either class; and ever since his time, no wide survey of cases has failed to reveal a considerable number of marginal forms which were neither normal nor limited to a two-color spectrum. These cases were long spoken of as "color-weak" or "incompletely color-blind," until Rayleigh's work (62) led to the conclusion that many of them were unequally sensitive to red and to green. The equation by which Rayleigh made this discovery,—the mixture of red and green to match yellow,—is commonly spoken of as the "Rayleigh equation." Ever since König's work (39) upon defectives of this type, they have been known by the name which he applied to them,—"anomalous trichromates," *i. e.*, persons whose color-system includes all three of the fundamental colors of Helmholtz (red, green and violet), but whose sensitiveness to red or green is abnormal. It is now customary (15, 37, 40, 42, 43, 52) to distinguish two groups of anomalous trichromates, upon the analogy of the two groups of dichromates,—the red-anomalous or protanomalous trichromates, whose sensitiveness to red is below normal, and the green-anomalous or deuteranomalous trichromates, whose

sensitiveness to green is below normal. Recent writers report other peculiarities of this group, the most marked of which is a heightened sensitivity to contrast. Guttmann[1] identifies color-weakness with anomalous trichromacy, claiming that the defect is a complex state involving seven inter-related symptoms. Nagel insists that color-weakness is the wider term,—that color-weakness may occur without the other symptoms of anomalous trichromacy being present.

It has been the purpose of the writer to examine the evidence upon which is based the assumption that the partially color-blinds are dichromates,—see only blue and yellow,—and to present a body of new experimental evidence upon the question of the color sensations of color-defectives.

A survey of the literature of color-blindness indicates that we are indebted to Herschel (21) for the first suggestion of the idea that the color-system of the color-blind is reduced to blue and yellow; and that the general acceptance of this idea is based upon the following lines of evidence (61):—

1. Testimony of the color-blinds themselves, and inference from color-confusions, from the naming of spectral colors and the colors of objects.

2. Color equations in which the various colors have been matched by mixtures of blue, yellow, black and white.

3. The study of acquired and temporary color defects.

4. The analogy of peripheral color-blindness.

5. The study of monocular cases of color-blindness. Of these five sorts of evidence, the last is by far the most important, since its evidence is direct.

But it seems very clear to the writer that *theory* has, in many cases, prejudiced the interpretation of the facts obtained from all five sources, and that we have no right to conclude from the evidence at hand that all typical cases of partial color-blindness are dichromates. Almost every writer who has had any wide experience with color defectives has seen mild cases of color-blindness, "incomplete" color-blindness, etc., in which the subjects give evidence of seeing some kinds of red or green; and the conviction seems to be growing common that dichromates are the extreme and not the typical forms of partial color-blindness,—that there are protanopes who see some greens, deuteranopes who see some reds, etc.

In view of the great importance attaching to monocular cases, it has seemed best to review all such cases available. After this the experiments performed by the writer upon a monocular protanope will be described; and the evidence derived from this study will be compared with the results of

[1]For the discussion of this question by Guttmann and Nagel, see the series of articles in the *Zsch. f. Sinnesphysiol.* 41-43.

similar experiments upon a number of color-blind subjects whose defect extends to both eyes.

B. Historical Cases of Monocular (red-green) Color-Blindness[1]

1. Woinow's case of green-blindness in one eye (1871)

The earliest case of monocular partial color-blindness known to the writer is that reported by Dr. N. Woinow (78) of Moscow in 1871. The patient, a woman 34 years old, was tested with rotating discs and her case was diagnosed as green-blindness. The following equations are reported:—

Left (normal) eye:

225 black + 135 white = 135 red + 125 green + 100 violet

Right (color-blind) eye:

220 black + 140 white = 105 violet + 255 red

310 black + 50 white = 30 violet + 330 green

Dr. Woinow evidently studied this case with the Helmholtz three-color theory in mind; but his equations seem to indicate that his patient was very deficient both in red and in green vision. The case was not so simple as this, however. The patient seems to have had an hysterical fear of reds, and both eyes appeared to be somehow sensitive to this color. She said she could not bear to look at red or orange, but that, if she had to do so, "she felt better" with her right (color-blind) eye closed. Moreover, she reported that when she looked with her right eye alone, "everything was tinged with red." Woinow concluded that she was color-blind to green only. But in view of the complications involved, and the small number of tests made, this case seems to have practically no value as evidence of the actual color sensations of the color-blind.

2. von Hippel's monocular partially color-blind subject (1880)

In the literature of the last thirty years, constant reference is made to the case of monocular color-blindness which was studied and described by von Hippel (28) in 1880. The subject, a young man, came to von Hippel for spectacles to correct double vision, and in von Hippel's exploration of the subject's right visual field with a Förster perimeter, constant confusions of red and green with yellow were noticed. Before this the subject had known nothing of his color defect. Von Hippel then made a long and careful series of experiments, using a Hoffmann spectroscope, Radde's international color

1 The monocular cases described by Niemetscheck (59), Holmgren (31), Kirschmann (35) and Piper (60) are intentionally omitted because this paper deals only with protanopia and deuteranopia.

charts, Holmgren's worsteds, Stilling's *pseudo-isochromatische Tafeln*, contrast shadows and tissue contrast, color equations with rotating discs, Dor's charts for the recognition of colors at a distance of five meters, and von Hippel's photometer with colored glasses. In all these experiments, the subject's left eye seemed perfectly normal, while with his right eye he made constant confusions of red and green with yellow, although occasionally using the words "red" and "green" correctly. In the experiments with the spectroscope, von Hippel reported that when the whole spectrum was shown at once the subject claimed to see red, yellow or greenish, and blue; but, when only a narrow band was shown, the whole warm-end of the spectrum was called yellow.

Von Hippel diagnosed his case as one of red-green blindness, and there seems little ground for questioning his decision. As he found no shortening of the spectrum, the subject was probably a deuteranope.

Holmgren (30) studied the same case, and diagnosed it as "a typical case of red-blindness," with shortened spectrum, and the two fundamental colors which such a case *should* have, according to the form of the Helmholtz theory presented in the first edition of the *Optik* (18),—a greenish yellow, and a blue tinged with violet.

Von Hippel (29) then made further experiments with the spectroscope, and substantiated his claim that the subject's spectrum was not shortened. He also carefully compared the subject's judgments of color made with his normal and his color-blind eye, and showed that he used "blue" and "yellow" for the same kinds of sensations in the two eyes. He added a series of experiments with negative after-images, in which the subject reported normal after-images for the left eye, but for the right gave blue as the color of all after-images from red, orange, yellow and green; yellow as the color of after-images from blue and violet.

On the whole, there seems good evidence that this subject saw only two colors (probably yellow and blue); and, as this was the first monocular case pointing clearly towards dichromacy, one can easily understand its importance.

Holmgren claims to have seen another case of monocular color-blindness in 1879, which, however, "unhappily became useless through an accident" (31).

3. Steffan's case of monocular color-blindness (15, 70, 73) (1881)

We get no clear light on our problem from this case. The patient was a man sixty-two years old, who showed defective color-vision in one eye after an attack of apoplexy. It is interesting to note that although, the patient showed lowered

sensitivity for all colors, the only color he completely lost was green; but considering our present uncertainty as to the relation of atypical acquired color-blindness to typical congenital color-blindness, we have no right to reason from the one kind to the other (38, 56, 71).

4. Kolbe's case of "monocular red-green weakness" (1882)

Kolbe (37b) used many of the same tests as von Hippel; and while this case does not show the grave color deficiency of von Hippel's case, repeated evidences of sub-normal color vision were found. No neutral band in the spectrum was established. But at 518 $\mu\mu$ the subject said at one time that the color was weaker than in the neighboring region; and at another time he reported that from 508 to 520 was an uncertain color. In the use of the Holmgren wools, the Stilling cards of 1879 and Dor's charts, the subject showed himself below normal, but considerably more color-capable than von Hippel's subject. In a series of tests of color sensitivity, Kolbe's subject showed decidedly high thresholds for both red and green. In the experiments with contrast shadows and negative after-images, this subject gave normal results for blue and yellow; but his reactions with red and green were practically those of a color-blind person.

From Kolbe's report, it would seem that this case might well be diagnosed as a mild case of color-blindness, although one hesitates to form such a conclusion without the use of color-equations, and a repetition of the spectral experiments.

Kolbe refers to a monocular case of "red-green" blindness described by Hermann (26a) in a pamphlet not accessible to the present writer. This subject's spectrum was shortened at the violet end,—the brightest region from 588 $\mu\mu$ to 583 $\mu\mu$, which appeared as a dull band, separating red, on the left, from green, on the right. These details seem to point rather to *violet*-blindness.

5. Schufelt's case of monocular color-blindness (67) (1883)

Following are the observations made upon "a healthy young man twenty-one years old" when tested with the Holmgren wools:—

"With both eyes open, he succeeded, without trouble or hesitation, in picking out a series of purples and greens to match the test shade; but he exhibited a good deal of uncertainty when called upon to do the same for the reds, the test color being a bright red-lead shade. The worsteds being again mixed up, he successfully chose the purple and green shades with either eye, one or the other being closed, and the

reds with the right eye, the left one being closed. The worsteds were mixed once more, and he was asked to close his right eye, and to pick out the red shades. This he essayed to do by first selecting a pale shade of brown, placing it on one side, and with considerable hesitation of manner, he proceeded in the same way until he had laid aside a full series of brown shades from dark to light ochre. It was amusing to see his confusion when I suddenly released his right eye, as the lids were kept together with my finger, and quickly closing his left, allowed him to see what he had done."

This case adds very little to our knowledge. One would hesitate to base any conclusions upon a preliminary test with the Holmgren worsteds. The case is included in this paper simply for completeness in reviewing the evidence.

6. A case of color-blindness limited to the nasal half of the left retina, described by Hess in 1890 (27)

A young man, thirty-one years old, found he had difficulty in distinguishing colors and thought his difficulty a matter of recent origin. Upon examination, it was found that on the nasal half of his left retina he was quite insensitive to red, and had a decidedly lowered sensitivity for the other colors, while on the other half of this retina, and on the whole of the other retina his color-vision was normal. Colors were presented simultaneously to the right and to the left of a given fixation-point; and he was asked to tell what colors he saw. His replies were as follows:

Normal (temporal) half of left eye	Color blind (nasal) half of left eye
Red appeared red	"dirty dark yellow"
Orange " orange	"dirty sulphur color"
Yellow " yellow	"yellow"
Yellow-green, normal	"weak yellowish grey"
Urgrün appeared "	"greenish grey"
Blue " "	"blue with violet tone"
Violet " "	"less saturated violet than that on temporal side"
Purple " "	"greyish violet"

Experiments with spectral lights gave similar results. It seems plain that this subject thought he saw *green* with his affected tract. In one place he especially said that "green looked neither yellow nor blue;" and since his other eye seems to have been completely normal, there is no apparent reason why he should use the wrong name for what he called "green."

In spite of the fact that the patient thought he saw green, Hess diagnosed the case as red-green blindness, explaining its

presence by the assumption that the red-green substance, posited by the Hering theory, was quite out of function. But one feels loath to accept this conclusion. The fact that the defect was limited to one half of one eye, and that the patient thought his difficulty a recent thing, would suggest that the case was possibly of central origin and acquired. Hence, whatever the results obtained by Hess, we ought not too readily to accept them as representative of typical partial color-blindness. And Guttmann (15, p. 280) has recently suggested that, under similar tests, a red-anomalous trichromate would have responded in much the same way, for, when small areas outside the fovea are simultaneously stimulated, the anomalous trichromate responds in much the same way as a patient who is typically color-blind.

7. Hering's case of monocular partial color-blindness (25) (1890)

In the same volume with the case just described, we find an account of a series of experiments by Hering upon a patient with partial color-blindness in one eye. The method of experimenting was practically the same: with a simple stereoscopic device he presented patches of color to the two eyes simultaneously, and asked the subject to compare them, and report what colors he saw with each eye. By means of mirrors, Hering was able to change the brightness and saturation of either color presented. Occasionally he tried, by increasing or decreasing the illumination, to present to the normal eye a color or a grey that should match the sensation experienced by the affected eye; but he gives no numerical values, and hence it is impossible to know exactly what his results mean, or to compare them with the results obtained from other subjects. To the affected eye, bluish red was reported to look "grey with a reddish shimmer;" spectral red, "dark yellowish grey;" orange, yellow and yellowish green, "whitish yellow;" *Urgrün*, "light grey;" ultramarine blue, "whitish blue;" and violet, "dark blue."

Upon the basis of these results, Hering diagnosed his case as one of red-green blindness, with weakened sensitivity for blue and yellow.

In a spectrum of moderate brightness, this patient reported three colors; yellow, green and blue. When the brightness was increased, only a "greenish shimmer" was mentioned, though the normal eye saw a beautiful saturated green. The spectrum was shortened at the red end,—the spectrum beginning at wave-length 630 $\mu\mu$ for the affected eye, while the normal eye saw color at 670 $\mu\mu$. From 630 $\mu\mu$ inward, the

patient saw only yellow with the affected eye, where red-orange and orange were visible to the normal eye.

Looking through a telescope at the spectrum, the patient described light of 630 $\mu\mu$ as yellow-red, but still more yellowish than it appeared to the normal eye; light of 600 $\mu\mu$ she described as orange; light of 570 $\mu\mu$ as cream colored. The lights from 500-420 $\mu\mu$ she described, sometimes as grey, at other times as greenish grey.

On the whole, Hering seems scarcely justified in calling this a case of red-green blindness, for in one test or another the subject correctly named both red and green. Guttmann (15, p. 279) suggests that this case also closely resembles red-anomalous trichromacy, and there is enough similarity to prevent our complete acceptance of the case as evidence for the claim that dichromates see only blue and yellow. Wundt (79, p. 229, note) says of these cases reported by Hess and Hering, "In these two cases we find complete red-blindness, while the sensitivity for green as well as for the other colors is merely lowered."

Of all the above cases, that of von Hippel alone furnishes evidence for the claim that partially color-blinds are dichromates. In Woinow's case, the results are complicated by the patient's emotional reaction to red, which she was supposed not to see; in Steffan's case there was probably some disturbance in the cortex, and in Hess's case there would seem to have been an acquired disorder of some kind; Hering's subject seemed to recognize all the colors when they were intense enough, and should perhaps be classed as a red-anomalous trichromate; the preliminary test performed upon Schufelt's case is suggestive but not conclusive. Von Hippel's subject was probably a dichromate, and von Hippel's work furnishes sufficient evidence that there can be clear-cut blue-yellow vision. But when one considers the great variation among color blind subjects which has constantly been noted by experimenters, one scarcely feels justified in jumping to the conclusion that *all* partially color-blind subjects see only blue and yellow. On the whole there seems good ground for the following confession of von Kries (40, p. 166):—"In general, one may well admit that the factual basis for the oft-made assertion that dichromates are blind to red and green but see yellow and blue, is very insufficient. In reality this claim is the result of theorizing, and its value is to be estimated according to its harmony with theory."

C. A NEW CASE OF MONOCULAR PROTANOPIA

During some work with colors in the year 1907-08, Miss G. S., a Senior in Mt. Holyoke College, made some remarks which

indicated that her color vision was not normal. Preliminary tests showed that she was quite unable to recognize reds with her right eye, while no lack of ability with this or any other color was shown when the left eye was tested.

She had studied psychology for two semesters before the following experiments were begun,—one semester of introductory text-book work and one semester of elementary laboratory work. She seemed to be an intelligent, careful observer of the "objective type." The experiments described below were performed in June, 1908, October, 1908, and November, 1909. The subject was in good health at each of these periods. In November, 1909, she was examined by a professional oculist, who reported that the ophthalmoscope showed nothing abnormal in either eye, but that she was slightly myopic in her left eye, and had some weakness of vision in the right eye which no lens seemed to correct. The subject reports that her maternal grandfather was color-blind, but she knows nothing about the details of his defect, and has never heard of any other case of defective color vision in her family.

1. Color confusions

a. Test with the Nagel cards (fifth edition)

With the left eye, the subject made no mistakes. With the right eye, she could see no red on any cards, and selected as grey A 9 (correct), and numbers A 3, 7 and 15 which have upon them red or red and grey dots. As green she selected the one green card A 5. In series B she thought the reds and browns were black and grey, but correctly named the green in B 3 and the yellow-green in B 1.

In the Nagel test, then, the subject showed herself blind to red, but made no mistakes in green. This is the more remarkable, because many persons who, upon further examination, show only slight defects in color discrimination make numerous confusions between green and grey.

b. Test with Bradley papers

Fifty pieces of Bradley paper, 3 cm. square, including all the standard colors and many tints and shades, with similar squares of the ten Bradley blacks, whites and greys, were spread upon a table in a good light. The subject stood before the table with her left eye covered. The test was conducted in the same manner as the Holmgren worsted test, the subject being given a sample and requested to select ten or a dozen pieces of paper of the same color. She selected green and yellow pieces to match the green sample (green yellow shade 2); four reddish pieces, one light orange, and six

greys to match the rose sample (red tint 2); and nine light and dark reds, four orange pieces and seven greys to match the red sample (red tint 1).

c. Tests with Holmgren worsteds[1]

Green A, presented to the right eye, was matched by worsteds 2, 4, 6, 8 and 12, all of which are green or yellowish green. 14, 16 and 18 looked like the sample to her, but darker. 10 and 20 seemed about the same in brightness as the sample, but bluer.

Rose B, presented to the right eye, was matched by 28, 32, 34, 36, 38 and 40, all of which have red in them, by the confusion colors 13, 15, 19, 33, 35, 37 and 39, all of which are browns and far removed from the rose sample, and by the confusion colors 1 and 3 which are faint greys with very little color of any kind in them. The grey 5, the light blue 21, and the bluish reds 22, 24, 26 and 30 were selected as like one sample, but "tending more or less toward blue." In these tests we have a strong indication of red blindness.

Red C, presented to the right eye, was matched by 32, 34, 36 and 38, all of which are reds. 40 looked like the sample but darker. In this test she made no color confusions.

In all of these tests, the subject refrained from holding the sample close to each bunch as she examined it, but, glancing at the sample and then at the other, decided by memory. In most cases she decided quickly and easily.

d. Tests with dots of Hering papers on grey cards[2]

In view of the fact that color-blindness has been reported (51, 52, 57, 68) to be sometimes more extreme at the fovea than elsewhere on the retina, a special series of experiments was performed to decide the point in this case. Thirty-two grey cards 8 cm. square were secured, and at the centre of each was pasted a round dot of Hering paper 4 mm. in diameter,—small enough so that when viewed directly at a distance of half a meter, only the fovea would be stimulated. The cards were spread out upon a table in a good light, and the subject, with one eye closed, was asked to pick out all the cards having a dot of the same color as one given as a sample. Hering papers 1-12 were each represented by two cards (except red no. 2 with which four cards were used), and upon 4 other cards dots of Hering grey no. 8 were pasted.

[1]Forty skeins with metal tag attached. Supplied by Chicago Laboratory Supply & Scales Co.

[2]Rothe papers made under Hering's direction.

With the right (color-blind) eye, Miss G. S. selected red and grey to match the red sample; purple, violet and blue to match the blue sample; green and yellow-green to match the green sample; and orange and yellow to match the yellow sample. There was no evidence that she was more color-blind at the fovea. With the left eye all the colors were correctly and exactly chosen and named.

e. Additional confusion tests

The subject stood before a window and looked skyward through colored films and glasses. The right eye was tested first. Blue, yellow and green were easily recognized; red looked dark grey, and all mixed colors which contained red lost their red element; blue-green looked greyish. With the left eye all the colors were correctly named. When a film or glass was moved over from the left to the right eye, the subject said it always looked darker.

A rough test was made to determine whether the subject used color associations in recognizing greens, etc. Seven black and white reprints of famous pictures were colored contrary to nature with crayons and water colors,—a face was painted a strong green, a cow purple, a tree red, four kittens were colored red, yellow, green and grey, a sky green, etc. With her right (color-blind) eye, the subject detected the trick in most cases, naming all the strong greens, yellows and blues correctly. None of the reds appeared to her to have color; and in those places where the green was weakened by the black of the print underneath the thin paint she failed to detect the green.

From these confusion tests one must conclude that this protanope is unable, under ordinary conditions, to see red as a color, but that under the same conditions she is repeatedly able to recognize and correctly name various kinds of green,—even such greens as those upon the Nagel cards. Now since this subject seems to have perfectly normal color sensitiveness with her left eye, we must assume that she knows what the sensation of green is like, and when she correctly insists that a certain color seen with her color-blind eye is green, we have very strong evidence for the conviction that green (as a specific color quality different from yellow and grey) is included in the color system of her protanopic (right) eye. At the same time, her occasional difficulty with greens gave evidence of a lowered sensitiveness for that color, and seems entirely consistent with the later discovery that there is a certain region in the neighborhood of the blue-greens which this subject confused with a light red.

2. *Experiments in color discrimination*

a. Determination of the color threshold with rotating discs[1]

Upon white discs with a radius of 95 mm. were pasted circular rings of the four standard Hering colors 5 mm. in width, at a distance of 60 mm. from the centre of the discs, one color being pasted upon each disc. Upon a fifth disc a strip of Bradley's neutral grey no. 2 was pasted, and this disc and a pure white one were interwoven with the discs bearing colors, and all mounted on the color-wheel together.

The subject was seated about one meter from the color-wheel, with her back to the source of light, and her left eye covered. The experimenter stood in front of the color-wheel when it was not in motion, to conceal it from the subject, in order that she might not know in advance what color was to be given. The experimeter would then draw out one of the colors or the grey, so that a small number of degrees were exposed, set the mixer rotating and ask the subject to name the colored ring. By varying the colors and the amount given, and by occasionally introducing grey to make sure that the subject was not merely guessing at the colors, a minimum amount was at length determined upon as the least amount of each color which the subject could correctly name. Frequent rests were given. After completing the series with the right eye, the experiments were repeated with the other eye.

TABLE I

Showing the Color Thresholds, as determined by means of rings of Hering paper upon white discs. (The determinations are expressed in degrees.)

			RED	GREEN	YELLOW	BLUE
Miss G. S.	Protanope	Right Eye	x	105	65	50
Miss M. S.	Deuteranope	Right Eye	110	x	40	25
		Left Eye	140	x	35	22
Miss H. E.	Deuteranope	Right Eye	270	320	200	210
		Left Eye	285	320	250	210
Miss G. B.	Deuteranope	Right Eye	230	225	250	205
		Left Eye	210	210	285	180
Miss E. C.	Deuteranope	Right Eye	315	350	270	180
		Left Eye	325	330	260	180
Miss I. B.	Deuteranope	Left Eye	148	180	55	90
Average of 40 eyes,—20 women who made no mistakes with the Nagel test			21	22	25	21

[1]It is a matter of considerable regret that it was impossible to use spectral lights for many of the experiments now to be reported upon. The recent work of Nagel, von Kries and their pupils shows the great advantage of such lights. But unfortunately the great cost of the apparatus necessary renders it unattainable in a small College laboratory. Rivers found the Lovibond Tintometer (44) very useful for quantitative determinations of the color sensitiveness of the natives of Torres Straits; but this apparatus, with a sufficiently large assortment of colored glasses, proved too expensive for us.

In the foregoing table the results obtained with Miss G. S.'s right eye are compared with the results of similar tests upon five deuteranopes, the last two of whom are mild cases; and with the results of tests upon normal eyes. An "x" in the table indicates that no color was recognized even when the whole ring (360°) was exposed to view.

Slight differences in the color sensitivity of the two eyes have been noted by many observers. Hence the eyes of all the subjects mentioned in this paper were tested separately, with the exception of the test with the Hegg sheet and the experiments in contrast. When there was not time to test both eyes, only the right was experimented upon, except in the case of Miss I. B. whose left eye was found to be weaker in color sensitivity than the right, and therefore more nearly comparable with the other subjects.

The foregoing experiment is subject to criticism upon the ground that the colors used were not the best ones for testing the color sensitivity of the color-blind. In making an equation of red and green with color-blind observers, it is often necessary to add blue to the red, or to the green, or to both these colors, in order to make them both appear grey. A second series of experiments was therefore performed using Hegg's pigments[1] instead of the Hering papers. Four discs 10 cm. in diameter were cut from Hering's grey paper number 14, and upon these discs rings 5 mm. in width were painted with Hegg's pigments, the rings being 60 mm. from the centre of the discs, as in the earlier tests. No. 14 grey was selected because that appeared to the writer and to two other normal observers to be the nearest in brightness to the grey upon the sheet of colors which is provided with the Hegg set.[2] Before the experiments upon the color threshold were begun, this sheet of colors was presented to Miss G. S., with the request that she name any colors she saw. Using her right eye, she at once named the blue and the green, but she recognized neither the red nor the yellow. The yellow she called grey, and said it was lighter than the grey band in the middle of the sheet; the red also seemed grey to her, but of the same brightness as the central grey. With her left eye she named the four "invariable" colors correctly, although she was at first a little uncertain about the yellow, and said it was a very poor yellow at best.

Table II presents the results of the tests with Hegg's pigments. The results with Miss G. S. are compared with those of

[1]Baird (4, p. 29) gives an account of the way in which these colors were decided upon.

[2]Unfortunately no apparatus for the exact evaluation of brightness was available in the laboratory.

five deuteranopes. Miss G. B. was not tested with the Hegg pigments, so the results of the Hegg test with another deuteranope, Mr. A. H. P., are substituted. The superiority of the Hegg red and green for a threshold test with color-blind subjects is clearly demonstrated. Evidently these colors approximate the neutral bands of the partially color-blind. The high thresholds for blue and yellow may possibly indicate a slightly decreased sensitivity for these colors; but in view of the difficulty which normal observers have in distinguishing them, when mixed with a considerable amount of bluish grey, it is perhaps unwise to come to such a conclusion as yet.

TABLE II

Showing the Color Thresholds, as determined by means of the Hegg pigments upon a grey background. (Results are expressed in degrees.)

			RED	GREEN	YELLOW	BLUE
Miss G. S.	Protanope	Right Eye	x	75	100	70
Miss M. S.	Deuteranope	Right Eye	240	x	x	110
		Left Eye	250	x	270	50
Miss H. E.	Deuteranope	Right Eye	x	x	x	240
		Left Eye	x	x	x	240
Mr. A. H. P.	Deuteranope	Right Eye	200	x	210	90
Miss E. C.	Deuteranope	Right Eye	x	270	x	315
		Left Eye	x	340	x	x
Miss I. B.	Deuteranope	Right Eye	x	55	x	125
		Left Eye	x	x	x	70
Average of 40 eyes,—24 women who made no mistakes with the Nagel test			57.1	74.6	98.8	71.6

For the general thesis of this paper, the most important point in this table is this, that almost all of these color-blind subjects recognized either red or green repeatedly, when a considerable amount was given, and Miss G. S. was sure of green at 75°,—about the average for normal observers.

The value of the Hegg pigments as confusion colors was further tested by showing the sheet of colors painted with the Hegg pigments to a considerable number of color-blind subjects with the request that they name the colors. This sheet measures 16 x 10 cm. Across the middle there is a band of neutral grey 2.5 x 10 cm; on each side of this band are two patches of color 5 x about 6.75 cm. in area, the red and the green being on one side, the blue and the yellow on the other. The following table, number III, shows how these colors were named. Of course, this test is of secondary importance, since a shrewd subject might readily assume that the four fundamental colors were displayed and then guess correctly which was red and which was green. In general, however, the subjects did not seem to think of this; and as the table shows, the grey band was several times reported to be colored.

TABLE III

Showing the names that were employed in describing the Hegg pigments

		RED	GREEN	GREY	YELLOW	BLUE
Miss G. S	Protanope	Grey	Green	Grey	Grey	Blue
Miss M. S.	Deuteranope	Pink	Grey	Grey	Brown	Blue
Miss E. C.	Deuteranope	Pink	Grey	Grey	Grey	Blue
Miss I. B.	Deuteranope	Red	Green	Grey	Yellow	Blue
Mr. A. H. P.	Deuteranope	Grey	Grey	Grey	Grayish-Yellow	Blue
Miss H. B.	Deuteranope	Grey	Grey	Grey	Brown	Blue
Mr. D. B. Y.	Deuteranope	Grey	Reddish	Grey	Grey	Blue
Mr. M. H. H.	Deuteranope	Grey	Green	Green	Brown	Blue
Mr. J. F. McD.	Deuteranope	Red(?)	Green	Pink	Yellow	Blue
Mr. A. B. C.	Deuteranope	Pink	Green	Green	?	Blue
Mr. C. R. B.	Deuteranope	Red	Brown	Grey	Red or Brown	Blue

b. Determination of the distance threshold for colors

Upon a sheet of Hering paper (no. 14 grey), four rows of squares were painted with the Hegg pigments,—three horizontal rows on the right half of the sheet, and one row at the middle of the left half. The sizes and colors of these patches were as follows:

	15 mm. blue, green, red, yellow.
2.5 mm. green, red, yellow, blue.	5 mm. red, yellow, blue, green.
	10 mm. green, blue, yellow, red.

The subject was stationed 14 meters from the card, with her left eye covered. She was asked to tell whether she saw any patches of color upon the grey sheet. As she could see none at that distance, she was asked to advance slowly until she could see some colored patch. At 3.5 meters she correctly named the largest blue square; at 2, the largest green square; and at 1.5, the largest yellow square. The smallest squares were recognized at 0.1 m. She wholly failed to recognize the red patches as colored.

TABLE IV.

Showing the distances at which small squares of colored paper were correctly identified (monocular vision)

DISTANCES (expressed in meters)	RIGHT EYE	LEFT EYE
14		15 mm. Red
13		
12		
11		15 mm. Green called Green or Blue
10		
9		
8.5		
8		15 mm. Blue; 15 mm. Yellow called White

7		
6.5		
6		15 mm. Yellow; 10 mm. Red
5.5		
5		
4.5		15 mm. Green; 10 mm. Blue; 10 mm. Yellow called White
4		10 mm. Green
3.5	15 mm. Blue	
3		10 mm. Yellow
2.5		
2	15 mm. Green; 10 mm. Blue	5 mm. Blue; 5 mm. Red
1.5	15 mm. Yellow; 5 mm. Blue;	5 mm. Green
1	10 mm. Yellow; 10 mm. Green;	5 mm. Yellow; 2.5 mm. Red
.5	5 mm. Yellow; 5 mm. Green	2.5 mm. Blue; 2.5 mm. Green 2.5 mm. Yellow
.1	2.5 mm Blue; 2.5 Green; 2.5 mm. Yellow	

A comparison of these results with the results of similar experiments upon twenty normal women and the six deuteranopes mentioned in Tables I and II shows that Miss G. S. occupies a middle position between the two groups in her recognition of green. Normal women recognize the largest green squares at 9 meters, and the smallest at 1.5 m; Miss G. S. recognized the largest green squares at 2 m. and the smallest at 0.1 m. Three of the deuteranopes did not recognize the green squares of any size at any distance; and the three who did recognize them succeeded at about the same distance as Miss G. S. When one remembers that this subject's visual acuity, in her color-blind eye, is somewhat below normal, it is quite surprising that she recognizes green so well. Possibly her inability to see yellow or blue at a distance is to be explained in the same way, although the deuteranopes also have considerable difficulty with these colors, especially in their recognition of the small squares. Miss G. S. did not appear to detect the red patches at all. In the tests with her left eye, Miss G. S. compares favorably with the normal women.

The experiments in color confusion showed very plainly that with her right eye Miss G. S. is color-blind to all kinds of reds tried, but that she fails to recognize green only when it is weak or mixed with blue. The experiments upon the color threshold and the distance threshold gave similar results. To the Hering and the Hegg reds the subject is quite blind; to both the Hering and the Hegg green, however, she seems to be sensitive, failing to recognize them only when they are quite reduced in saturation, or at a considerable distance from her eye. Her color threshold for green is conspicuously lower than that of the other color-blind subjects. It would seem then that if the subject is blind to any kind of green, presented in saturated form, it must be of a somewhat different tone

from the Hering, Hegg, Holmgren, Nagel and Bradley greens. In the color equations to be described later, the particular green to which this subject is insensitive was determined. But it is already pretty obvious that this subject's color sensations are not limited to blue and yellow. If her two eyes were defective, one might perhaps explain her recognition of green from an employment of secondary criteria of some kind, such as we have to assume (10, 71) in subjects who repeatedly recognize greens and reds in experiments with colored papers, but are able to see only yellow and blue in the spectrum. But since Miss G. S. sees the colors normally with her left eye, she has a clear consciousness of green as a quality distinct from yellow or grey; and when she uses the word "green" to describe the sensations aroused by stimulation of her right (color-blind) eye, we must assume that she sees green as green.

c. Campimetry experiments

Preliminary experiments were performed with Hering papers. The standard red, yellow, green, and blue were placed upon a color mixer one at a time, and rotated behind a grey screen, through which a hole 15 mm. in diameter had been cut. Upon the screen were pasted strips of millimeter paper, leading away from the hole in four directions. The subject fixed her gaze upon a pencil point which was moved outward or inward. The results showed coincidence of the green with the yellow and blue zones, and relatively constricted color areas in the right eye.

Further tests were made with the Hegg pigments by means of a small perimeter. In these tests the stimuli were always introduced first at the extreme periphery, and every precaution was taken to prevent the subject from anticipating which color was to be presented. The left eye showed the normal color zones, and is quite comparable with the eyes of five normal women tested in the same way. The right eye again showed coincidence of the green with the yellow and blue zones, and constricted color areas. It is, of course, possible that in the outer color zone this subject confused green with yellow, though one would rather expect that this green would there appear grey, as it does to normal eyes. The matter is further complicated by the fact that the subject repeatedly recognized it as green. Blue also was twice called "green." The red disc was called "white" and seen far out beyond the color zones. Yellow and green were called "white" on the extreme periphery, but blue was twice seen first as "black."

d. Contrast and Negative After-Images

Ever since Stilling's suggestion, in the seventies, that contrast shadows might be successfully used for the diagnosis of color-blindness, many experimenters have tested the ability of the color-blind to obtain contrast colors (6, 15, 75) and colored after-images.[1] The writer has used various methods with Miss G. S. and the other subjects,—contrast rings upon rotating discs, tissue contrast (grey strip on a color, all covered over with tissue paper), the Hering contrast box after Ragona Scina's method, and negative after-images from colored patches of Hering paper 9 cm. square, upon grey cards 40 x 50 cm., the after-images being projected upon grey cards with a black fixation dot in the centre. The following Table shows the results, *i. e.*, the colors induced in the various experiments.

TABLE V

Showing the color-names which were employed in describing the induction effects in the contrast and after-image experiments

		RINGS	TISSUE	HERING BOX	NEGATIVE AFTER-IMAGES
Miss G. S.	Prot.	Blue Yellow	Blue Yellow		Blue Yellow
Mr. J. W. P.	Prot.			Blue and Yellow	
Miss E. C.	Deut.	None	None	Blue and Yellow	
Miss I. B.	Deut.	Blue Yellow			
Miss H. B.	Deut.	Blue Yellow		Blue and Yellow	
Mr. D. B. Y.	Deut.			Blue and Yellow	Blue Yellow

In general, these subjects seemed to be less sensitive to contrast than normal observers. Occasionally a subject would report a slight tinge of pink or green as an induced color, but from the other experiments upon the same subjects it seemed more likely that the words were used by chance, as color names are so often used by such persons. Generally blue was reported as the contrast color both for red and for green, though often only a brightness contrast was noted.

e. Rapidity of color discrimination

Miss G. S., the monocular protanope, and four of the women deuteranopes were tested for rapidity in sorting into 6 piles, 60 pieces of Milton Bradley paper 30 mm. square, mounted on pieces of white cardboard 88 mm, square.[2] All five subjects sorted tints and shades of blue and yellow more rapidly than

[1]Von Hippel (29) and Guttmann (16) report blue and yellow after-images from all colors.

[2]This test is modeled after that described by Henmon (20).

tints and shades of red, orange-red and green. Miss G. S. made the typical confusions with reds, putting them all in one pile which she called "black;" but she correctly sorted and named the greens, confusing only the darker shade of green with the standard green. The other subjects, also, showed considerable ability in recognizing and correctly sorting reds and greens. Of course, it is possible that in all such cases the color-blind is assisted by secondary criteria, and to make this test of real value colors should be used which are nearer to the reds and greens which the color-blind calls grey, such as the Hegg pigments. But even then one should have a slightly different set for protanopes and deuteranopes in order that the reds and greens may appear to be greys of equal brightness.

f. Experiments with Spectral Lights

(1). With the Schmidt and Haensch direct-vision spectroscope

The subject was first asked to look through the spectroscope toward a cloudy sky, and read off in wave-lengths the limits of all the colors she could see with her right eye. But she was unable to do this, because the lenses provided with the spectroscope were not suited to correct her visual defect.[1]

A collection of pieces of Hering paper 4 cm. square (including 2 pieces of each of the 12 colored papers, and grays 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50) was then spread out upon a table; and, using only the right eye, the subject was asked to select papers like those seen in the spectroscope and arrange them in the same order.[2] After looking into the spectroscope several times, the following papers were chosen and arranged in the order given:—50 grey, 20 grey, 5 grey, yellow 5, green-yellow 6, green-blue 8, blue 10 and violet 11. From these results it seems highly probable that the red-end of the spectrum is colorless and shortened, and that she may have seen some green. Of course, there is the alternative that she *remembered* that green comes between yellow and blue in the spectrum; but then we must admit that she sees green in the colored papers.

When the papers were mixed up again, and the experiment was repeated with the left eye only, she put two squares of red 2, and one of yellow 5, in place of the greys at the red-end of the series.

The Schmidt and Haensch spectroscope was found to be a very convenient instrument for roughly determining whether or not a subject's spectrum was shortened at the red-end.

---

[1] See test by optician mentioned above p. 378.

[2] In 1878 Magnus (45) recommended the matching of spectral colors with Holmgren wools to avoid the use of color names.

TABLE VI

Showing the length of the Spectrum, and the Colors which it was reported to contain. The numerical data are expressed in $\mu\mu$. All determinations were made with the right eye

		LIMIT	RED	ORANGE	YELLOW	GREEN	BLUE	VIOLET
Miss G. S.	Prot.	?	Grey	Yellow	Yellow-Green	Yellow-Green	Green-blue	Violet
Mr. J. W. P.	Prot.	620		"	Yellow	Yellow	Blue	Blue
Miss M. S.	Deut.	650	Red	"	Yellow	"	Blue	"
Mr. C. R. B.	Deut.	650	Red	"	Green or Yellow	?	Blue or Purple	Blue or Purple
Mr. G. W. B.	Deut.	650	Yellow	"	Yellow	Yellow	Blue	Blue
Miss E. C.	Deut.	650	Red	"	"	"	Blue	"
Mr. A. B. C.	Deut.	640	Orange or Yellow	"	"	"	Violet	Violet
Mr. M. H. H.	Deut.	650	Red	"	Red	Red	Blue	Blue
Mr. J. F. McD.	Deut.	650	Green	"	Green	Green	Blue or Violet	Blue or Violet
Mr. C. D. R.	Deut.	650	Red	"	Yellow	Yellow	Blue	Blue
Mr. A. H. P.	Deut.	650	Yellow	"	"	"	Blue	"
Mr. F. B. S.	Deut.	650	Red	"	?	Green	Purple	Purple
Mr. D. B. Y.	Deut.	650	Red	"	Yellow	Yellow	Purple	"

And while the subject was using the instrument, the experimenter asked what colors were visible. None of the subjects claimed to see more than three colors, although several of them recognized the instrument and knew what colors they ought to see. No great importance is attached to the use of color names in the following table, although several of the subjects who claimed to see colors other than blue and yellow showed a similar ability to distinguish these colors in other experiments. Other experimenters (28) have noted the tendency of color-blind subjects to see three colors when the whole spectrum is shown at once; and it was a matter for regret that our instrument had not an attachment for exposing one color at a time.[1] Table VI gives the results of these experiments.

(2). *Viewing a petroleum flame through a spectroscope*

It was attempted to determine the length of Miss G. S.'s spectrum by having the subject set the instrument in such a position that all color appeared at the right of the vertical line across the centre of the field of the spectroscope. The setting of the instrument was read off in degrees. The instrument was then adjusted until all color was at the left of the vertical line. The following table shows the results obtained.

TABLE VII

Showing the Limits of Visibility in the Spectrum. (Results expressed in terms of our scale readings.)

			RED END	VIOLET END
Miss G. S.	Right Eye,	Protanopic	285°	282° 9′
	Left Eye,	Normal	285° 40′	281° 28′
Miss M. S.	Right Eye,	Deuteranopic	285° 33′	281° 21′
Miss L. D.	Right Eye	Normal	285° 40′	281° 40′
Mr. S. P. H.	Right Eye	Normal	285° 26′	281° 25′

The typical shortening at the red end is plainly seen in the case of Miss G. S.'s protanopic right eye; there would seem to be a shortening at the violet end also.

(3). *Experiment with bisulphide of carbon prisms*

A wide beam of light was sent from an electric lantern through two slits and then through two bisulphide of carbon prisms[2] placed side by side in a darkened room. The two spectra produced, were interrupted at two meters by a screen in which two slits had been cut, so that on the next screen beyond, two patches of colored light could be seen, each 6 cm. high and 1 cm. wide. The prisms rested upon discs of card-

[1]Cohn (7, pp. 84 f.) describes such an instrument.

[2]Made by Wm. Gaertner & Co., Chicago, Ill., Cat. No. L, 4025.

board, which were held in place by thumb tacks pushed through the centre of each. These discs could be rotated easily to right or left; and by this means the colors seen on the farthest screen could be changed from red to violet. The movements necessary to cause these changes in color were so slight that the vividness of the colors was not materially affected; and in the case of red, green, blue and violet, the colored patch was approximately monochromatic. Yellow always had a fringe of orange an one side, or of green on the other.

The subject was seated in front of the last screen, about one meter from it, where she could not see any colors except those shown in the two patches.

As a preliminary experiment, the subject was asked to close her left eye, and name the colors shown her. Only one prism was used in this experiment. This prism was turned so that the extreme red appeared on the farther screen. The subject reported no color, so the prism was very slowly rotated until the subject said she saw "yellow." The colors then in the patch were yellow and orange. The prism was then moved slowly again; and as soon as the yellow began to turn greenish, the subject said she saw "green." She continued to report green until that color was no longer visible to the experimenter, and then she at once said she saw "blue," which she continued to report well out into the violet. The subject was then asked to rest her eyes, and the prism was turned back until the patch was a strong pure red. The subject was now asked to tell what she saw, and she replied that she saw a patch of "grey."

α. *Color comparison with two prisms*

The subject turned away from the screen, and both prisms were illuminated. The left prism was set so that it gave a pure green patch, the right prism at the extreme red. The subject was then asked to look at the screen with her right eye only, and report what she saw. She replied that the left patch was green and the right grey. She was then instructed to watch the patches and tell when they looked just alike. The right prism was then slowly turned, and not until both patches were pure green did the subject judge them alike. Evidently it was impossible to match spectral green with spectral red or yellow of any kind.

The subject turned away from the screen again; the left prism was now set at red, and the right at the extreme violet. She reported that she saw grey at the left and faint blue at the right. The right prism was slowly turned, with frequent stops, but she was not satisfied with the match until this prism also gave a pure red patch. In this test the attempt to match

red with blue-green, green or yellow was unsuccessful. No attempt was made to equate brightnesses; the subject insisted throughout that there was a qualitative difference.

These experiments with spectral lights emphasize the same fact that was indicated in the experiments with colored papers and the Hegg pigments,—that the subject is blind to red, but not blind to green.

β. Determination of the Color Threshold with Spectral Lights

Only one prism was illuminated, and an episkotister was set up just beyond the screen with the slits in it. The prism was turned to give pure green on the patch, the episkotister set at 5° and rotated by means of an electric motor. The subject was asked to look with her right (protanopic) eye at the screen where the left colored patch had appeared in the earlier experiments. She reported that she could see nothing. She closed her eye and the episkotister was set at 10°. The subject now reported that she saw green, although there had been no intimation on the part of the experimenter that green would be the first color shown. The prism was moved back and forth, but she could recognize no other color. The episkotister was set at 8, 6 and 4 degrees in successive tests; but below 10° the subject saw no color. At 6° she claimed she saw a faint line of light when the prism was turned to green.

The episkotister was again set at 10°, and the prism moved back and forth; green alone was recognized. At 15° no other color was seen. The episkotister was opened 5° at a time, in successive tests, and the prism turned through the series of colors, with each new opening. At 30°, blue was recognized and at 55°, yellow.

No definite attempt was made in these experiments to attain dark adaptation in the right eye. There was considerable light in that part of the room where the lantern was stationed; and in most of the experiments the subject gazed about freely during the intervals between tests. In this particular series of tests, however, the subject was asked to close her eye while the episkotister was being adjusted, so that she might not see what changes were being made. The conditions, then, were favorable for dark adaptation, and we cannot say with certainty whether the extreme brightness of the green was merely a manifestation of the Purkinje phenomenon in dim light, or the displacement of the maximal brightness which we would expect of a protanope even without dark adaptation.

The experiment was repeated with the left eye only, and all four colors, red, yellow, green and blue, were repeatedly recognized and correctly named at 5° opening.

Of course these experiments with a home-made spectral apparatus are open to the grave criticism that no provision was made for determining objectively just what lights were given to the subject,—instead of a statement of the exact wave length of the patches of color exposed, the reader has only the writer's assurance that red, green, etc., were given. But the apparatus necessary to conduct this experiment objectively was too expensive to be bought from the funds of a small laboratory; and since the results of these rough tests are quite in harmony with those obtained by the use of colored papers, they certainly add considerable weight to the total mass of evidence in favor of the view that this protanope is not blind to green. It should also be said that repeated tests have shown the experimenter's color sense to be perfectly normal, so that there is no possibility that wrong colors were given by mistake.

From the experiments thus far described, certain conclusions regarding the color sensations of Miss G. S. seem amply justified. There can be no doubt that her right eye is totally insensitive to the quality *red*. She never used the word *red* to describe any sensations obtained through her right eye, in any of the experiments. It seems equally clear that her right eye is not insensitive to the quality *green*. With scarcely a single error, she repeatedly recognized green in the Nagel cards, the Holmgren worsteds, the Milton Bradley and Hering papers, in gelatine films, in prints painted with water colors, in spectral lights, and in the Hegg pigments. And since she is familiar with the quality *green*, through the use of her normal left eye, we must grant that the sensation which she correctly names "green", when her right (protanopic) eye is stimulated, is probably the same sensation-quality which normal persons describe by the use of the *term* "green." In other words, her spectrum is not reduced to blue and yellow, although in general she shows the ordinary characteristics of protanopia. When the greens used are reduced in saturation or in brightness, however, or when only a very small patch of color is presented, Miss G. S. shows herself somewhat less sensitive to green than normal persons. She shows a slightly subnormal sensitivity for blue and yellow also; but these colors are less affected than green.

It is considerably more difficult to decide whether the other subjects see either red or green as normal persons do. There is, of course, no doubt that color-blind subjects can distinguish many reds and greens from each other and from yellows and blues. Some of the subjects mentioned in this paper showed a good deal of facility in distinguishing colors, so that from day to day the writer hesitated whether or not to class

them as color-blind. This decision was, however, somewhat simplified by a change in mental state on the part of several of the doubtful subjects. Misses H. E. and E. C., for instance, long maintained that it was ridiculous to class them as color-blinds, insisting that they could distinguish the reds and greens one encounters in the daily use of colored objects, even though they could not always correctly name the weak colors with which they were tested in the laboratory; but after a considerable number of equations had been made, and the results exhibited to them,[1] these subjects took a more calm and objective attitude in the matter, frankly giving themselves up to the task of ascertaining just how much their color sense was affected, and even recounting instances in which their friends had detected their errors in the naming of colors. In order to eliminate the "secondary criteria" by which such subjects are supposed to distinguish colors,[2] as many as possible of these subjects also were tested with spectral lights, using an arrangement of apparatus similar to that used with Miss G. S. But a lime light was substituted for electricity, the experiment was performed in a dark room, and the carbon bisulphide prisms were placed one above the other with a movable slit in front of each to give the different colors. Three of the subjects,[3] the protanope and two deuteranopes, reported only blue and yellow; red, yellow and green all looked alike to them, but no equation between red and blue-green could be made, because the blue-green was reported to be whitish and lacking in the yellowish tinge which they saw in the red. These three subjects, however, are extreme cases of color-blindness. Misses E. C. and I. B. insisted that they saw red as a color distinct from yellow, and repeatedly recognized it. Miss I. B., whose color defect is the least marked of all the cases reported in this paper, recognized green also with quite as much certainty as the extreme cases did blue and yellow. And since these two subjects are the ones who have showed the greatest keenness in distinguishing reds and greens in the other tests, one must interpret this as another indication that only extreme cases of partial color-blindness are limited to blue and yellow.

3. Color Equations

a. Equations with the Hering color sense apparatus[4]

This apparatus is so constructed that the subject, on looking

[1]Following Maxwell's suggestion (46, p. 287) the subjects were occasionally requested to look at their equations through a colored glass. The inequality in the mixtures thus demonstrated helped greatly in inducing the objective attitude.

[2]Differences in brightness, saturation, color associations, etc. 10 p. 210.

[3]Mr. J. W. P. (protanope), Mr. D. B. Y. (deuteranope), and Miss H. B. (deuteranope).

[4]This instrument is described and figured by Hering (24).

down a dark tube may see a disc one half of which is colored by light filtered through one colored glass, the other half by a mixture of lights transmitted through two glasses. The intensity of the color presented is varied by the amount of light reflected through the colored glasses from movable reflectors, whose position is indicated upon a dial. It is thus fairly easy to form color equations, such as red = green + blue, etc.; and to read off from the dial the amount of light passing through each glass. When fully open the reflectors register 120 units. The following table shows the result of the experiments with this apparatus upon Miss G. S. and various other subjects.

TABLE VIII

Equations with the Hering Color Sense Apparatus. (Results are expressed in degrees, 120 being the maximum reading possible)

		GREEN =	RED +	BLUE	RED =	GREEN +	BLUE
Miss G. S.	Prot. R.	40	120	120	120	60	120
Mr. J. C. H.	Deut. R.	30	70	90			
	Deut. L.	30	62	90			
Miss M. S.	Deut. R.	40	120	75	60	120	50
	Deut. L.	30	120	95	35	120	90
Miss H. E.	Deut. R.				80	60	120
	Deut L.				60	50	120
Miss G. B.	Deut. R.	50	45	120	120	120	120
	Deut. L.	80	85	120	120	120	30
Miss H. B.	Deut. R.	120	120	0			
Mr. D. B. Y.	Deut. R.	120	120	0			
Miss E. C.	Deut. R.	120	55	120	120	120	120
	Deut. L.	120	120	120	120	120	120
Miss I. B.	Deut. R.				33	25	35
	Deut. L.	20	55	20	120	50	80
Miss L. W.	Deut. R.	120	25	50			
	Deut. L.	120	40	60			
Mr. J. W. P.	Prot. R.	108	120	30			

The wide variation in the results for different subjects can probably be partly accounted for by differences in the amount of sunlight on different days, or at different hours of the day.[1] But the constant insistence of many subjects, besides the monocular protanope, that they saw red or green when more than a certain amount of either color was used, gives added evidence that many color-blind are not dichromates. Miss G. S. was very sure she saw green when 50 was given alone, or 70 mixed with blue.

The instrument would be greatly improved if four glasses could be used at the same time, so that blue could be mixed both with red and with green simultaneously. The subjects

[1]A series of experiments upon Miss H. E. (Deut.) extending over 5 days in the spring of 1909 showed a variation of from 20 red on a bright day, to 120 red on a dark day.

were told that a colorless equation was to be made; and the small amounts of red or green allowed when given alone may be attributed to the natural confusion of these colors with yellow, and the insistence that the single glass should appear colorless. A slight admixture of blue would obviate this difficulty. But the small amount of red or green allowed by some subjects, when mixed with a large amount of blue, remains as evidence for the main thesis of this paper,—that red or green sensations may be possible to the partially color-blind.

It seems quite likely that the neutral grey bands of different deuteranopes may occupy slightly different regions of the spectrum (40, p. 158). If this is the case, those whose bands are most nearly represented by the particular red and green glasses of the Hering apparatus would accept a much larger amount of red or green when given alone in this instrument.

b. *Equations obtained with rotating discs*

Ever since Maxwell's work (46, 47) with rotating discs in the fifties, it has been customary to make color equations which shall indicate the extent of color confusion to which color-blind subjects are liable, and to determine whether all colors can be matched by the mixture of blue and yellow, black and white.

(*1*). *The Rayleigh equation*

It is commonly asserted (41, 64) that all equations which hold for normal observers will be found to hold also for the partially color-blind. From a theoretical point of view, one would expect that deuteranopes, at least, who are blind to both red and green, would accept all normal equations; and the writer found that all the deuteranopes tested with such equations did accept them. But in protanopia, the shift of maximum brightness might be expected to vitiate the equation somewhat. It was mainly to test the validity of this assumption that Miss G. S. was tested with the equation red + green = yellow; but the unexpected result of the experiment led to the testing of a number of the other subjects in the same way.

The normal Rayleigh equation,—the equation accepted on a bright day by a number of normal, trained observers, from which 30 untrained observers varied by only about 10 degrees,—was presented to the subject. Miss G. S. found the mixture much too green, and was not satisfied until the green was reduced to 63°. All the other subjects accepted not only the normal equation, but also wide variations from it. The following table gives the normal equation with the

Hering papers, the equation formed for Miss G. S. and the extreme amounts of red and green accepted by the other observers. The amounts of yellow, black and white are omitted, as not pertinent to the question.

TABLE IX

Rayleigh equation of color-blind subjects

			RED +	GREEN =	YELLOW +	WHITE +	BLACK
Normal Equation			175	185	33	49	278
Miss G. S.	Prot.	R.	297	63	70		290
			Extremes allowed by other color-blind subjects				
			RED +	GREEN	RED +	GREEN	
Mr. J. W. P.	Prot.	R.	300	60	0	360	
Miss M. S.	Deut.	R.	315	45	90	270	
Miss H. E.	Deut.	R.	225	135	110	250	
	Deut.	L.	225	135	75	285	
Miss E. C.	Deut.	R.	182	178	65	295	
	Deut.	L.	190	170	95	265	
Miss I. B.	Deut.	R.	192	168	160	200	
	Deut.	L.	190	170	125	235	
Miss L. W.	Deut.	R.	190	170	160	200	
	Deut.	L.	200	160	160	200	
Miss H. B.	Deut.	R.	190	170	130	230	
Mr. D. B. Y.	Deut.	R.	300	60	0	360	
Mr. A. H. P.	Deut.	R.	178	182	50	310	

The wide variation in the amounts of red and green accepted in the Rayleigh equation by these subjects is in striking contrast with the results obtained with Miss G. S. who would not allow a variation of more than 5° in the green. In this she resembles the anomalous trichromates discovered by the use of this equation, as she does also in her sensitiveness to green in the other experiments. But in view of the fact that, unlike them, she is completely lacking in sensitivity to red, has a neutral band in the blue-green (*cf.* the experiments with the Hering color-sense apparatus p. 395), and appears to get no contrast colors nor after-images from red or green, she would seem to be more properly classed with the protanopes than with the anomalous trichromates. Nagel (52) reports a similar experience with the Rayleigh equation, in comparing his own vision with that of two normal observers. Their equation, made up of about 180° each of red and of green, seemed very red to him, and had to be changed to between 140 and 150 red on a dark day, and to between 89 and 95 red on a bright day. His variation was then hardly more than that of Miss G. S.

It will also be noticed that some subjects show a much wider variation than others. The subjects who vary between the widest limits in this equation are the subjects who made the worst confusions of colors in the other tests, and have therefore been classed by the writer as extreme cases of color-blindness.

The subjects whose Rayleigh equations did not exhibit such wide variations are those who have shown such keen sensitivity to reds and greens that it has often seemed absurd to class them as color-blinds in spite of the fact that they signally fail in such tests as those of Nagel, Holmgren and Stilling, and accept an equation in which a weak bluish red is matched with a weak bluish green upon the color mixer. These cases remind one of Holmgren's "incompletely color-blind" (31, 33, pp. 40-41); their acceptance of the normal Rayleigh equation excludes them from the group of anomalous trichromates.

All the subjects objected to wider extremes of red and green by correctly naming red or green when either one was increased beyond the limits finally decided upon; they insisted that the mixture was different in quality from the dirty yellow with which it was being matched, no matter how the yellow mixture was varied. Now, since dichromates are supposed to see red and green as yellow, it is difficult to imagine how they were able to detect the reds and greens under the conditions, unless we grant the possibility that they may have some sense of red and green as a color quality distinct from yellow.

(2). *The dichromate equation*

The confusion of red with green has, from the beginning, been regarded as one of the chief peculiarities of the color-blind; but it was soon observed that, even in extreme cases of color-blindness, the subject did not confuse all greens and all reds. It is now well established that those reds and greens which, like the physiological primaries, have a bluish tinge, and are somewhat unsaturated, are most likely to be confused, since they both appear colorless to the color-blind. In the dichromate equation, the attempt was made to make an equation in which green was declared to be identical with red, adding to both sides as little blue, black and white as possible. The following table gives the results of these tests.

TABLE X

Dichromate equations

			RED	+BLUE	+WHITE	=GREEN	+BLUE	+BLACK	+WHITE
Miss G. S.	Prot.	R.	360			38	22	300	
Mr. J. W. P.	Prot.	R.	262		98	330	30		
Miss M. S.	Deut.	R.	230	55	75	360			
Miss H. E.	Deut.	R.	290		70	300		45	15
Miss G. B.	Deut.	R.	210	50	100	270	90		
Miss H.Y.B.	Deut.	R.	210	45	105	280	80		
Mr. A. H. P.	Deut.	R.	300		60	220		140	
Mr. D.B.Y.	Deut.	R.	232	40	88	260	35	65	
Miss E. C.	Deut.	R.	100	73	187	107	53		200
Miss I. B.	Deut.	L.	50	55	255	85	55		220
Miss L. W.	Deut.	R.	50	200	110	198	45	87	30

The most striking point in this table is the very small amount of green allowed by Miss G. S. When more was introduced, she at once objected to it, insisting that the mixture then had a greenish tinge. As the subjects were kept in complete ignorance in regard to the changes made in these equations, it is difficult to understand how she could repeatedly make correct judgments, if she did not see green somewhat as normal persons do.

The relatively small amounts of red and green allowed by the last three subjects is also striking. When more red or green was added, they were quite as sure of the change as was Miss G. S. in the case of green; and no increase in the amount of blue served to cancel the additional red or green, as one would expect if red and green appear yellowish to these subjects. To be sure, other tests have shown that these three subjects are mild cases of color-blindness; but such cases are quite valuable for the main contention of this paper, that people properly classed as color-blinds have some sensations of red and green.

(3). *Monocular comparison of colors*

In order to test still further the claim that all colors perceived by the color-blind can be matched by mixtures of blue and yellow, and at the same time to obtain a full statement of the appearance of the different colors, each of the Hering papers was rotated before Miss G. S.'s protanopic right eye, and matched by a mixture of colors rotated before her left eye. Two color-mixers were set up and operated behind a screen, and the subject looked through two blackened cardboard tubes 6 cm. in diameter and 55 cm. long. In this way she saw only the standard papers with her right eye and only the mixtures with her left. The results appear in the appended table.

TABLE XI

Showing how the Hering papers appear to a protanopic eye

	WHITE	BLACK	YELLOW	YELLOW-GREEN	GREEN	BLUE-GREEN	BLUE
Red No. 1	35	325					
Red No. 2	10	340	10				
Orange 3	75	170	115				
Y-Orange 4	105	62	193				
Yellow 5	50	175	135				
Y-Green 6	12	22	55		271		
Green 7	13	32		150		165	
B-Green 8	42	68			130		120
Blue 10	68	78					214
Violet 11	20	265					75
Purple 12	70	220					70

In this experiment, the colors were presented to the right eye in random order; and in each equation, the attempt was made to match the color presented to the right eye by a mixture of black and white with yellow or blue. Green was introduced only after every effort to make an equation without it had failed, and green had been insisted upon by name. As the table shows, there was no need of red to match red or orange. This experiment then gives additional evidence in support of our contention that this protanope perceives green but not red.

A long series of color equations was formed for two deuteranopes, Misses M. S. and H. E., in which the attempt was made to match mixtures of red and yellow, red and blue, green and yellow, and green and blue, by mixtures of blue and yellow with black and white. In these tests, the equations were formed by the use of large and small discs on a single color-mixer, and the mixtures to be matched were given in irregular order, a few at a time, through a period of three weeks. In the case of Miss M. S. green was not distinguished at all; but red was regularly distinguished from yellow and grey mixtures whenever a large amount of red was used, even though the red was mixed with considerable yellow or blue. Miss H. E. recognized both red and green when presented in large quantities.

In order to gather upon a single page a large part of the evidence for the contention that partially color-blinds are not dichromates, excepting in extreme forms of the defect, the following table has been constructed. In the vertical column are given the tests which seem of most importance for this question, and which were used with a considerable number of subjects. Under the initials of each subject, R. or G. is used to indicate that the subject showed considerable ability in recognizing red or green under the conditions of the various experiments mentioned; "con." indicates that the subject made the typical color-blind confusions, though occasionally distinguishing red or green correctly. The proportion of confusions to recognitions gives a fair idea of the degree of the color-blindness in each of the subjects. Miss G. S., Prot., distinguished green in practically every test, and the other women all recognized red or green (or both) repeatedly; the three men appeared to use the color names capriciously, although occasionally applying them correctly. They are probably as insensitive to both red and green as Miss G. S. is to red and Miss M. S. is to green.

The Stilling plates were not obtained until after the first four women mentioned in this Table had left college. Thirteen color-blind subjects have been tested with these plates, one

TABLE XII

Summarized Statement showing the Comparative Data obtained from the various observers. In this Table, Con. expresses the fact that the observer generally confused red and green color-stimuli in the test or tests indicated, while the initials R., G., express the fact that the observer recognized red or green fairly well under the conditions of the experiment.

	PROTANOPES		DEUTERANOPES								
	G. S.	J. W. P.	D. B. Y.	M. S.	H. E.	G. B.	H. B.	A. H. P.	E. C.	I. B.	L. W.
Nagel Cards	G.	Con.	Con.	Con.	R.	R.	Con.	Con.	R.	Con.	R.
Holmgren Worsteds	G.	Con.	Con.	Con.	Con.	R. G.	R.		Con.	Con.	
Stilling's Plates		Con.	Con.	Con.			Con.		R. G.	Con.	
Hering Color-Sense Apparatus	Con.	Con.	Con.	Con.	Con.	Con.	Con.		Con.	R. G.	R.
Color Threshold (Hering Papers)	G.			R.	R. G.	R. G.			Con.	R. G.	
Color Threshold (Hegg Pigments)	G.			Con.	Con.			Con.	Con.	Con.	R.
Hegg Sheet	G.		Con.	R.			Con.	Con.	R.	R. G.	
Spectroscope (Schmidt & Haensch)	G.	Con.	Con.	R.				Con.	R.		
Spectrum (Bisulphide of Carbon Prisms)	G.	Con.	Con.	Con.			Con.	Con.	R.	R. G.	
Rayleigh Equations	G.	Con.	Con.	Con.	R. G.		R.		Con.	R. G.	R. G.
Dichromate Equations	G.	Con.	Con.	R.	R. G.	R. G.	R.	Con.	R. G.	R. G.	R. G.

protanope, Mr. J. W. P., nine men and three women deuteranopes. All except two of these subjects read Plates *4 and 12* correctly, though according to Stilling (72, p. 11) deuteranopes should read only 4 and 13-15, protanopes only 1, 12, and 13-15. Five of these deuteranopes read some figures in Plate 1; and three read parts of 5, 6, 7, 8 and 9. Mr. J. W. P. (Prot.), read 1, 12, 13-15; Miss E. C. was the only subject who had real difficulty with 12. She read parts of Plates 1, 2, 3, 4, 5, 6, and 8, and the whole of Plates 13-15.

D. Conclusions

What, then, must be our conclusion regarding the color-system of the partially color-blind? How many qualitatively different sensations of color does he possess? From a study of the literature, no less than from an experimental investigation of numerous cases of defective color-vision, the writer has been convinced that partial color-blindness is not identical with dichromatism. The statement that sensations of blue and of yellow alone are possible to the partially color-blind cannot be reconciled with our findings. A brief review of the evidence which has been brought forward in the literature, in support of the contention that dichromatism is identical with partial color-blindness, will make our position clearer.

1. Certain color-blinds, who have made a careful study of their color-systems, have declared that they are limited to sensations of blue and of yellow (Dalton, Pole). Opposed to this is the testimony of five of our observers (Misses M. S., H. E., G. B., E. C., and I. B.) that red and green are specifically different color qualities from yellow and grey.[1] There are doubtless cases of defective color vision where only sensations of blue and of yellow are possible. Of our observers, Messrs. J. W. P., D. B. Y., and A. H. P., probably belong to this extreme type of defective, which is represented by Dalton and Pole. But this conjecture does not justify the inference that all partial color-blinds belong to the extreme type. The evidence which has been presented in this paper supports the contrary view,—that many intermediate or transitional stages and degrees of abnormality may be found to exist between dichromatism and normal color-vision,—and that, moreover, these intermediate forms need not be identical with anomalous trichromatism.

[1]Nagel (52, p. 32) came to the conclusion that he, a deuteranope, saw red as a specific sensation-quality when an extra-foveal region was adequately stimulated; and Schumann (68) reports that he also, a deuteranope (?), can see red as red, and can distinguish it from yellow. But Guttmann (15) classes Schumann as a green-anomalous trichromate.

This view is further supported by the inferences which may be drawn from our findings regarding color confusions and color naming. The repeated recognition of greens and of reds throughout, and even under relatively unfavorable conditions, furnishes a body of indirect evidence which cannot be ruled out of court by assuming the participation of secondary criteria.

2. When reds and greens were presented under favorable conditions of stimulation, many of our observers have wholly failed to match them with mixtures of yellow, black and white. When the conditions of stimulation are unfavorable, reds and greens may be matched with such mixtures, or with each other, if blue be added to one or to both. But when a considerable amount of red or of green was employed, the red or the green was seen in the mixture by all of our less pronounced cases of color-blinds, and by certain of the extreme cases, even when every precaution was taken to eliminate the influence of 'chance' and of 'guessing.' The evidence which is furnished by our color equations, then, points to the existence of specific sensations of red and of green in the color-systems of the less pronounced cases of color-blindness.

3. This paper has included no data derived from an examination of acquired and temporary defects of color vision. In the opinion of the writer, it is premature and unsafe to seek for analogies between these atypical cases and cases of congenital color-blindness, although Stilling (71) seems to advocate such a procedure. The findings of other investigators, however, (38) raise a significant question, whose ultimate solution promises to support the thesis of the present paper. If sensitivity to green may lapse before sensitivity to red is lost, and if transitional forms between trichromatism and dichromatism occur in acquired color-blindness, what theoretical warrant can there be for refusing to believe that an analogous series of transitional forms occurs in congenital color-blindness? The less pronounced cases which we have described would fit into such a series.

4. Light is thrown upon the general problem of abnormal color-systems by a consideration of the phenomena of indirect vision. Recent explorations of the peripheral retina (4, pp. 53 f.) have yielded results which support the thesis of the present paper,—that retinal function lapses, when it does lapse, in a gradual and not in an abrupt fashion. "The whole retinal surface, with the exception of the macula and the blind spot, is endowed with a similar function, to the extent, at least, that no region possesses a capacity which is wholly lacking in any other region. The color sensitivity of the periphery is unquestionably less acute than that of more central areas; and in consequence of this diminished sensitivity

a constant stimulus may arouse different sensations at different regions. It cannot, however, be said that any part of the normal retina, save the macula and the blind-spot, is wholly or even partially color-blind. For the whole manifold of sensation qualities which any region is capable of furnishing may, under appropriate conditions of stimulation, be furnished by every other region." (4, p. 65.)

5. Cases of monocular color-blindness constitute the crux of the whole question. Our review of the monocular cases which have been reported in the literature showed that, with the exception of von Hippel's, they reveal nothing but meagre experimentation, glaring contradiction, and theoretical bias. A survey of Table XII (p. 401 of this paper) shows, in striking form, the trend of the evidence which has been obtained from a study of Miss G. S. Green was recognized, and its specific quality was insisted upon, in almost every experiment with spectral colors, as well as with pigments,—colored papers, glasses, gelatines, etc. There can be no justification for the statement that she sees only blue and yellow. Yet she is clearly a protanope, and not an anomalous trichromate. If we grant that von Hippel's patient saw only blue and yellow, must we not also grant that Miss G. S. sees green, blue and yellow? This assumption is supported by abundant indications that many others of our color-blinds possess a similar sensitivity to red or to green.[1]

There seems, then, to be a large mass of evidence, direct and indirect, which attests the presence of sensations of red and green in the color systems of the partially color-blind. The reader who still insists that partial color-blindness is identical with dichromatism must find some means of explaining away this mass of evidence. It seems much more reasonable to admit that a strict classification of color defectives is necessarily artificial; to assume the existence of slight degrees of variation from normality, and numerous transitional forms between normality and total color-blindness; and to regard dichromacy as an extreme variation, and not as a typical condition of the partially color-blind.

E. Bibliography

Selected bibliography of books and articles of importance in connection with the particular problem of this paper. For more extended references see Helmholz's *Optik* for the older literature, and the various periodical indices for the newer writings.

1. Abney, W. deW. Colour Vision. New York. (No date.) The Tyndall Lectures delivered at the Royal Institution in 1894.

[1] Nagel (57) reported that among thirty dichromates, both protanopes and deuteranopes, who were recently examined by him, none failed to recognize various shades of red when a sufficiently large area of the retina was stimulated.

2. ALLEN, FRANK. Persistence of Vision in Color-blind Subjects. *Phy Rev.*, 1902, 15, 193-225.

3. ANGIER, ROSWELL P. Vergleichende Bestimmungen der Peripheriewerte des trichromatischen und des deuteranopischen Auges. *Zsch. f. Psychol.*, 1904, 37, 401-413.

4. BAIRD, J. W. Color Sensitivity of the Peripheral Retina. Washington, Carnegie Institution, 1905.

5. BAIRD, J. W. The Problems of Color-blindness. *Psychol. Bull.*, 1908, 5, 294-300.

6. COHN, H. Der Simultankontrast zur Diagnose der Farbenblindheit. *Centralbl. f. prakt. Augenheilk.*, 1878, 2, 35-36.

7. COHN, H. Ueber Farbenblindheit. *Centralbl. f. prakt. Augenheilk.*, 1878, 2, 84-85, 264.

8. DONDERS, F. C. Ueber Farbensysteme. *Arch. f. Ophthalm.* (*Graefe*), 1881, 27, I, 155-223.

9. DONDERS, F. C. Noch einmal die Farbensysteme. *Arch. f. Ophthalm.* (*Graefe*), 1884, 30, I, 15-90.

10. EBBINGHAUS, H. Grundzüge der Psychologie. 2nd Ed. Leipzig, Veit, 1905, 1, 209-212.

11. EDRIDGE-GREEN, F. W. Colour-Blindness and Colour-Perception. 2nd Ed. London, Kegan, Paul, Trench, Trübner & Co., 1909.

12. FAVRE, A. Résumé des mémoires sur le Daltonisme. 1877.

13. GUTTMANN, A. Untersuchungen am sogenannten Farbenschwachen. *Bericht d. I, Kong. f. Exp. Psy.*, 1904, 6-10.

14. GUTTMANN, A. Ein Fall von Grünblindheit (Deuteranopie) mit ungewöhnlichen Complicationen. *Zsch. f. Sinnesphysiol.*, 1906, 41, 45-56.

15. GUTTMANN, A. Untersuchungen über Farbenschwäche. *Zsch. f. Sinnesphysiol.*, 1908, 42, 24-64, 250-270; 43, 146-162, 199-223, 255-298.

16. GUTTMANN, A. Anomale Nachbilder. *Zsch. f. Psychol.*, 1910, 57, 271-292.

17. HELMHOLTZ, H. von. On the Theory of Compound Colours. *Phil. Mag.*, 1852, (4) 4, 519-534.

18. HELMHOLTZ, H. von. Handbuch der physiologischen Optik. Leipzig, Voss. 1856-1866.

19. HELMHOLTZ, H. von. Handbuch der physiologischen Optik. 2nd Ed. Leipzig, Voss. 1885-1896.

20. HENMON, V. A. C. The Detection of Color-blindness. *J. of Phil., Psychol. etc.*, 1906, 3, 341-344.

21. HENRY, W. C. Memoirs of the Life and Scientific Researches of John Dalton. 1854. Pages 25-26 give Herschel's letter to Dalton, written in 1833.

22. HERING, E. Zur Lehre von Lichtsinne. Wien, Carl Gerold's Sohn, 1874. 2nd. Ed. 1878.

23. HERING, E. Zur Erklärung der Farbenblindheit aus der Theorie der Gegenfarben. *Lotos*, N. F. 1880, 1. Auch separat, Prag, 1880.

24. HERING, E. Zur Diagnostik der Farbenblindheit. *Arch. f. Ophthalm.* (*Graefe*), 1890, 36, I, 217-233.

25. HERING, E. Die Untersuchung einseitiger Störungen des Farbensinnes mittelst binocularer Farbengleichungen. *Arch. f. Ophthalm.* (*Graefe*), 1890, 36, III, 1-23.

26. HERSCHEL, J. F. W. Remarks on Colour Blindness. *Phil. Mag.*, 1859, (4) 19, 148-158.

26a. HERMANN, G. Ein Beitrag zur Casuistikder Farbenblindheit, Inaug. Diss. Dorpat, 1882.

27. HESS, C. Untersuchungen eines Falles von halbseitiger Farbensinnstörung am linken Auge. *Arch. f. Ophthalm.* (*Graefe*), 1890, 36, III, 24-36.

28. Hippel, A. von. Ein Fall von einseitiger, congenitaler Roth-Grünblindheit bei normalem Farbensinn des anderen Auges. *Arch. f. Ophthalm.* (*Graefe*), 1880, 26, II, 176-186.
29. Hippel, A. von. Ueber einseitige Farbenblindheit. *Arch. f. Ophthalm.* (*Graefe*), 1881, 27, III, 47-55.
30. Holmgren, F. Ueber die subjective Farbenempfindung der Farbenblinden. *Centralbl. f. d. med. Wiss. Berlin*, 1880, No. 49, 898-900, No. 50, 913-916.
31. Holmgren, F. How do the color-blind see the different colors? *London Roy. Soc. Proc.*, 1881, 31, 302-306.
32. Huddart, J. An account of persons who could not distinguish colours. *Phil. Trans.* 1777, 67, 260-265.
33. Jeffries, B. Joy. Color-blindness: its dangers and detection. Boston, Houghton, Osgood & Co., 1879.
34. Jennings, J. E. Color-Vision and Color-Blindness. Philadelphia, Davis, 1896.
35. Kirschmann, A. Beiträge zur Kentniss der Farbenblindheit. *Phil. Stud.*, 1893, 8, 173-230, 407-430.
36. Kirschmann, A. Normale und anomale Farbensysteme. *Arch. f. d. ges. Psych.*, 1906, 6, 397-424.
37. Koffka, Kurt. Untersuchungen an einem protanomalen Systeme. *Zsch. f. Sinnesphysiol.*, 1909, 43, 123-145.
37b. Kolbe, B. Ein Fall von angeborener einseitiger Rothgrünschwäche, *Centralbl. f. prakt. Augenheilk.* 1882, 6, 291-296.
38. Köllner, H. Zur Entstehung der erworbenen Rotgrünblindheit. *Zsch. f. Sinnesphysiol.*, 1910, 44, 269-292.
39. König, Arthur und Dieterici, Conrad. Die Grundempfindungen in normalen und anomalen Farbensystemen und ihre Intensitätsverteilung im Spectrum. *Zsch. f. Psychol.*, 1893, 4, 241-347.
40. Kries, J. von. Die Gesichtsempfindungen. Nagel's Handbuch der Physiologie des Menschen. Braunschweig, 1905, 3, 109-282.
41. Ladd-Franklin, C. Vision. Baldwin's Dict. of Phil. and Psy., New York, 1902, 2, 765-799.
42. Levy, Max. Ueber einen zweiten Typus des anomalen trichromatischen Farbensystems nebst einigen Bemerkungen über den schwachen Farbensinn. Diss. Freiburg i. B., Speyer and Kaerner, 1903.
43. Lotze, Arthur. Untersuchungen eines anomalen trichromatischen Farbensystems. Diss. Freiburg i. B., Kuttruff, 1898.
44. Lovibond, J. W. Measurement of Light and Color Sensations. London, Geo. Gill and Sons, 1893.
45. Magnus, H. Zur spectroskopischen Untersuchung Farbenblinder. *Centralbl. f. prakt. Augenheilk.*, 1878, 2, 80-81, 233-235, 287.
46. Maxwell, J. C. Experiments on colour, perceived by the eye, with remarks on colour-blindness. *Edin. Trans.*, 1855, 21, 275-297.
47. Maxwell, J. C. Account of Experiments on the Perception of Colour. *Phil. Mag.*, 1857, (4) 14, 40-47.
48. Müller, G. E. Zur Psychophysik der Gesichtsempfindungen. *Zsch. f. Psychol.*, 1896, 10, 1-82; 1897, 14, 1-76, 161-196.
49. Müller, G. E. Die Theorie der Gegenfarben und die Farbenblindheit. *Bericht d. I, Kong. f. Exp. Psy.*, 1904, 6-10.
50. Nagel, W. A. Ueber dichromatische Farbensysteme. Vortrag geh. i. d. 29. Vers. der Ophthalm. Gesellsch. zu Heidelberg, 1901. Wiesbaden, Bergmann.
51. Nagel, W. A. Dichromatische Fovea, trichromatische Peripherie. *Zsch. f. Psychol.*, 1905, 39, 93-101.
52. Nagel, W. A. Fortgesetzte Untersuchungen zur Symptomatologie und Diagnostik der angeborenen Störungen des Farbensinns. *Zsch. f. Sinnesphysiol.*, 1906, 41, 239-282, 319-337.

53. NAGEL, W. A. Versuche mit Eisenbahn-Signallichtern an Personen mit normalen und abnormem Farbensinm. *Zsch. f. Sinnesphysiol.* 1907. 41, 455-473.
54. NAGEL, W. A. Zur Nomenklatur des Farbensinnsstörungen. *Zsch. f. Sinnesphysiol.*, 1907, 42, 65-68.
55. NAGEL, W. A. Einführung in die Kenntnis der Farbensinnstörungen und ihre Diagnose. Wiesbaden, Bergmann, 1908.
56. NAGEL, W. A. Ueber typische und atypische Farbensinnstörungen nebst einem Anhang: Erwiderung an Herrn Dr. A. Guttmann. *Zsch. f. Sinnesphysiol.*, 1908, 43, 299-314.
57. NAGEL, W. A. Farbenumstimmung beim Dichromaten. *Zsch. f. Psychol.*, 1909, 44, 5-17.
58. NAGEL, W. A. Tafeln zur Untersuchung des Farbenunterscheidungs-vermögens. Wiesbaden, Bergmann. Sechste Auflage, 1909.
59. NIEMETSCHECK. Ueber Farbenblindheit. *Prag. Vierteljahrsschr.* 1868, 25, IV, 224-238.
60. PIPER, H. Beobachtungen an einem Fall von totaler Farbenblindheit des Netzhautzentrums im einen und von Violettblindheit des anderen Auges. *Zsch. f. Psychol.*, 1905, 38, 155-188.
61. POLE, W. On the Present State of Knowledge and Opinion in regard to Colour Blindness. *Trans. Roy. Soc. Edin.* 1893, 37, 441-480.
62. RAYLEIGH. Experiments on Colour. *Nature,* 1881, 25, 64-66.
63. Report of the Committee on Colour Vision. *Roy. Soc. Proc.*, 1892, 51, 281-396.
64. RIVERS, W. H. R. Vision. Schäfer's Text-Book of Physiology, London, 1900, 2, 1026-1148.
65. ROOD, O. N. Colour, A Text-Book of Modern Chromatics. 4th Ed. London, Kegan, Paul, Trench, Trübner and Co., 1904.
66. ROSMANIT, J. Zur Farbensinnsprüfung im Eisenbahn- und Marinedienste. Wien, Braumüller, 1907.
67. SCHUFELT, S. W. A case of Daltonism affecting one eye. *N. Y. Med. Rev.*, 1883, 23, 319.
68. SCHUMANN, F. Ein ungewöhnlicher Fall von Farbenblindheit. *Bericht der I. Kong. f. exp. Psy.*, 1904, 10-13.
69. SEEBECK, A. Ueber den bei manchen Personen vorkommenden Mangel an Farbensinn. *Pogg. Ann.*, 1837, 42, 177-233.
70. STEFFAN, PH. Beitrag zur Pathologie der Farbensinnes. *Arch. f. Ophthalm.* (*Graefe*), 1881, 27, II, 1-24.
71. STILLING, J. Ueber Entstehung und Wesen der Anomalien des Farbensinnes. *Zsch. f. Sinnesphysiol.*, 1910, 44, 371-427.
72. STILLING, J. Pseudo-Isochromatische Tafeln zur Prüfung des Farbensinnes. Leipzig, Geo. Thieme. Dreizehnte Auflage, 1910.
73. THOMPSON, W. and WIELAND, C. Detection of Color-Blindness. Norris and Oliver's System of Diseases of the Eye. Phila., Lippincott, 1900, 2, 315-352.
74. TITCHENER, E. B. Text-Book of Psychology. New York, Macmillan, 1910, 80-85.
75. TSCHERMAK, Ueber Contrast und Irradiation. *Ergebnisse d. Physiol.*, 1903, 2, 726-798.
76. TUBERVILLE, D. Several remarkable cases in physick, relating chiefly to the eyes. Phil. Trans., 1684, 14, 736.
77. WILSON, G. Researches on Colour-Blindness. Edin., Sutherland and Knox, 1855.
78. WOINOW, M. Zur Diagnose der Farbenblindheit. *Arch. f. Ophthalm.* (*Graefe*), 1871, 17, II, 241-248.
79. WUNDT, W. Grundzüge der physiologischen Psychologie (5th. Ed.), Leipzig, Engelmann, 1902, 2, 226-232.